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ABSTRACT

The processes of photosynthesis and respiration are basic to the understanding of many other aspects and functions of biological systems. Because of their curricular significance, these processes served as the focal point in an investigation of student conceptions and instructional effectiveness. In this study, students in a college nonscience majors' biology course took tests designed to reveal their conceptions of respiration and photosynthesis before and after course instruction. Even though most students had taken at least one full year of biology, serious misconceptions persisted. Most students gave definitions of respiration, photosynthesis, and food which were markedly different from those generally accepted by biologists. These incorrect definitions were associated with more fundamental misunderstandings about how plants and animals function. Most students could not explain how animal cells use either food or oxygen. They understood plants as vaguely analogous to animals, taking in food through their roots instead of mouths. Previous biology instruction seemed neither to improve student performance on the pretest nor to prepare them to master these conceptions during the course. Course instruction was more successful, but misconceptions persisted for many students. These results raise fundamental questions about the effectiveness of curriculum and instruction in current high school and college biology courses. (Author/ML)

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Research Series No. 164

THE EFFECTS OF INSTRUCTION ON COLLEGE NONMAJORS' CONCEPTIONS OF RESPIRATION AND PHOTOSYNTHESIS

Charles W. Anderson, Theresa H. Sheldon,
and Joann DuBay

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Abstract

Students in a college nonscience majors' biology course took tests designed to reveal their conceptions of respiration and photosynthesis before and after course instruction. Even though most students had taken at least one full year of biology, serious misconceptions persisted. Most students gave definitions of respiration, photosynthesis, and food which were markedly different from those generally accepted by biologists. These incorrect definitions were associated with more fundamental misunderstandings about how plants and animals function. Most students could not explain how animal cells use either food or oxygen. They understood plants as vaguely analogous to animals, taking in food through their roots instead of mouths. Previous biology instruction seemed neither to improve student performance on the pretest nor to prepare them to master these conceptions during the course. Course instruction was more successful, but misconceptions persisted for many students. These results raise fundamental questions about the effectiveness of curriculum and instruction in current high school and college biology courses.

THE EFFECTS OF INSTRUCTION ON COLLEGE NONMAJORS' CONCEPTIONS OF RESPIRATION AND PHOTOSYNTHESIS[1]

by Charles W. Anderson, Theresa Sheldon, and Joann DuBay[2]

This is a study of how students entering a college, nonmajors' biology course understood the processes of respiration and photosynthesis, of how their understanding was influenced by previous biology courses that they had taken, and of how their understanding changed as a result of instruction in the course. The study reported in this paper was part of a larger curriculum development effort which led to the development of instructional modules on five other topics besides respiration and photosynthesis (Anderson, 1985; Bishop, Roth, & Anderson, 1985).

We chose to focus on the related processes of respiration and photosynthesis because of their curricular significance. These processes play central roles in biologists' understanding of many aspects of living systems. For example, our digestive systems, circulatory systems, and respiratory systems all function as they do largely because of the needs of our body cells to engage in respiration. Similarly, the demands of photosynthesis dictate many characteristics of plant structure and function. Even more important, an understanding of photosynthesis and respiration is a prerequisite for any systematic understanding of ecology. Food chains and food webs begin with photosynthesis and end in respiration. Photosynthesis and respiration are the

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[1]This paper was presented at the annual meeting of the American Educational Research Association held April 1985 in Chicago.

[2]Charles W. Anderson co-coordinates the Middle School Science Teaching Project. He is an assistant professor with Michigan State University's Department of Teacher Education. Theresa H. Sheldon was an undergraduate in elementary education. She has since earned her BA from Michigan State University (MSU) and now teaches in California. Joann DuBay is an undergraduate in special education at MSU.

essential processes in the most basic of all matter cycles: the carbon cycle. The reactants for one process are the products of the other, so that matter cycles endlessly through the two processes. The cycling of matter serves a more fundamental purpose, however, for photosynthesis and respiration play essential roles in the flow of energy through ecosystems. It is through photosynthesis and respiration that the energy in sunlight is captured and made available to support metabolic processes in all living organisms.

Perhaps because of its curricular significance, students' understanding of the process of photosynthesis has been investigated by a number of previous researchers, including Wandersee (1983), Simpson and Arnold (1982), and Roth, Smith and Anderson (1983). In combination, these studies have investigated conceptions of photosynthesis in a variety of different populations ranging from fifth grade to college. The findings of these studies tend to be quite consistent, showing that the majority of students at all levels hold important misconceptions about photosynthesis similar to those described in this paper. We know of no previous studies on student conceptions of cellular respiration.

In reading the studies of conceptions of photosynthesis, the similarity in responses among students of different ages is often striking. Achieving a scientific understanding of photosynthesis seems to be a remarkably slow process, especially considering that most students take courses in biology that include instruction about photosynthesis. Is instruction in biology really as ineffective as the data seem to indicate? One purpose of this study is to investigate this question.

The primary purposes of the study are as follows:

1. To describe college nonmajors' conceptions of how plants and animals acquire and use matter and energy, including the roles of respiration and photosynthesis, and

2. To assess how those conceptions are affected by high school and college biology teaching.

Method

Subjects

The subjects for this study were 105 university sophomores, juniors, and seniors enrolled in a nonmajors' biological science course. Most were pursuing degrees in elementary education. A survey of their science backgrounds indicated that most had completed at least one high school or college level biology course; about half had completed a course in chemistry or physics, usually high school chemistry.

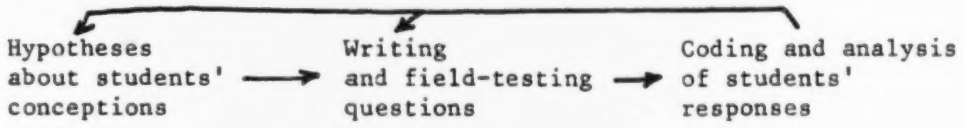
Written Test

The primary data source for the study was a written test designed to probe students' understanding of respiration and photosynthesis. A copy of the test is attached to this paper as an appendix. The test questions asked students to define terms such as respiration and photosynthesis in their own words, to explain how plants and animals get food and energy, and to explain how they see various biological processes and concepts as related. The final version of the test contained thirteen questions, including both open-response and multiple choice items.

The test was administered as a pretest and posttest to students enrolled in the course during three different terms over nine months. Students taking each test were a random sample of the students attending class. Data collected during the fall term were used primarily to revise our hypotheses about important issues and to develop test items. Thus most quantitative analyses reported in this study are based on data collected during the winter and spring terms. The pretest was taken by 105 students and the posttest by 94 students during the last two terms of the study.

Development of Test Questions

The written test was developed using the cycle illustrated below. Each step in the cycle is explained in the following paragraphs.


Hypotheses about students' conceptions
Writing and field-testing questions
Coding and analysis of students' responses

Hypotheses about students' conceptions. The development of the test began with a set of hypotheses about students' conceptions of respiration and photosynthesis. The hypotheses were based on other researchers' descriptions of students' conceptions and on our own previous work with fifth-grade students.

Writing and field-testing of questions. Individual test items were generated which we expected would reveal students' understanding of respiration and photosynthesis. Some of these items were modifications of items used previously by us or by other researchers. Other items were generated to test our hypotheses about the nature of student thinking. A pilot version of the test containing these items was then administered.

Coding and analysis of students' responses. A system for coding student responses was developed for each question, based on our hypotheses about the conceptions addressed by the question and on the students' actual responses. Each set of codes identified acceptable responses and several categories of students' naive responses. Reliability of coding procedures was established by having two individuals independently code the same sample of tests. Discrepancies in codes were analyzed and coding procedures modified to increase the consistency of coding decisions.

Revision of hypotheses and test items. The coded data were used in conjunction with data from clinical interviews to revise our hypotheses about students' conceptions and to rewrite test items to make them more effective in addressing specific issues. The final version of the test was the result of three such cycles of analysis and revision.

Student Background Questionnaire

Each student taking the pretest also filled out a questionnaire about previous science courses in high school and college. Student responses to this questionnaire provided data about their previous coursework in biology.

Clinical Interviews

During the initial phases of the study, clinical interviews were conducted with seven students before and after instruction. A modified stimulated-recall technique was used in which students were shown their written test and asked to recall their thinking at the time they responded to each test item. During postinterviews, they were also asked to describe how their thinking had changed as a result of instruction.

The interviews were transcribed and used to check the validity of the tests. We compared our coded test data with the interview transcripts to determine how well the written tests and coded responses corresponded to the much more extensive explanations of students' thinking that were generated during the interviews.

Nature of Instruction

The tests and interviews that provided the data base for this paper were developed as a part of a curriculum development project funded by the Fund for the Improvement of Postsecondary Education. This project led to the development of an instructional module (Bishop, Roth, & Anderson, 1985). In its

finished form, the module explains and illustrates common misconceptions about respiration and photosynthesis held by college nonscience majors. It includes laboratory activities and other materials for students and instructors that are designed to confront those misconceptions and contrast them with scientifically accepted conceptions. During the period when the data reported in this paper were collected, the module was still under development; various pilot versions were in use.

Actual instruction included lectures, laboratory activities, and discussions in laboratory sections. Although the course instructors used the pilot versions of the module, they used them in different ways. Some instructors emphasized the contrast between naive and scientific conceptions and used the materials to make students aware of their own thinking. Others used the materials in a more traditional manner, focusing on the concepts to be learned rather than the contrast between naive and scientific views. This paper, therefore, does not present a well-controlled comparison between different instructional techniques. The data, however, do allow some preliminary assessments of the effects of instruction on student conceptions.

Analysis of Test Responses

Data analysis began with a process of developing defensible interpretations of student responses to test items. We did not wish to develop global scores that somehow measured the total amount of students' knowledge. Instead, our aims were more descriptive. We wished to (a) develop valid descriptions of student conceptions and (b) develop methods of classifying students as to their beliefs in a particular conception.

The first task, developing valid descriptions of student conceptions, began with the generation of hypotheses before the development of the first pilot test. These hypotheses were continually refined and modified throughout

the test development and analysis process, as described above. The conceptions described in this paper are the end result of that process, the product of several analyses and revisions.

The second task, classifying students according to their understanding, began after the final descriptions of student conceptions had been developed. At that point it was necessary to relate student written test responses to our descriptions of student conceptions. The process necessarily involved inference and interpretation, since the students themselves were not aware of their own theories or belief systems, and thus could not describe them directly. Sample student answers and our interpretations of them are included at several points in this paper.

The inferences and interpretations were based on coded student responses. The coding procedure (described in DuBay, 1984) distinguished between student responses that were consistent with scientific thinking about each test item and several categories of naive student responses. Because generally more than one test item addressed each conceptual issue, a system was developed for classifying students on the basis of patterns of responses on all the items relevant to an issue. This procedure classified students as (a) demonstrating full knowledge of the scientific conception, (b) demonstrating partial knowledge of the scientific conception, (c) demonstrating no knowledge of the scientific conception, or (d) unclassifiable, usually due to missing data.

In summary, the analysis of test responses produced the following information:

1. Descriptions of student misconceptions and contrasting scientific conceptions for several conceptual issues,
2. Coded data classifying student responses to each test item, and
3. A system for classifying students according to their understanding of each scientific conception, based on patterns of responses to one or more test items for each conception.

Assessing Effects of Instruction

The effects of previous biology instruction were assessed by classifying students according to the amount of previous biology they reported having taken. The amount of previous instruction was then crosstabulated with student understanding of each scientific conception.

The effects of instruction in the course were assessed by comparing student understanding of each scientific conception as demonstrated on the pretests and on the posttests.

Results

The results section of this paper is divided into two parts. The first part describes student conceptions of photosynthesis and respiration. The second part assesses the effects of instruction in previous biology courses and in the course on which this study was based.

Student Conceptions of Respiration and Photosynthesis

Our description of student conceptions of respiration and photosynthesis is divided into two parts. First, we discuss students' definitions of three concepts that are essential to a biological understanding of this topic: respiration, photosynthesis, and food. Second, we describe underlying conceptual difficulties with students' understanding of how plants and animals obtain matter and energy.

Definitions of important terms. Among the items on the test were questions asking students to define three important terms: respiration, photosynthesis, and food. The definitions offered by most students for these terms were quite different from the biological definitions. Biological and student definitions for each term are contrasted below.

1. Respiration. The process of respiration, as it is understood by biologists, involves both a sequence of chemical reactions and an energy conversion. The sequence of chemical reactions combines glucose with oxygen to produce carbon dioxide and water.[3] At the same time, chemical potential energy in the glucose is released and converted to heat or to chemical potential energy in another compound, ATP. Put more simply, respiration is the process by which all aerobic organisms obtain energy from food.

However, when we asked them to define respiration, *none* of the students taking the pretest mentioned glucose or any related compound. Only 5% mentioned food. Only 16% mentioned energy. Over 80% of the students gave definitions such as the following in response to Question 1 (see appendix):

> Exhaling CO_2 for humans, exhaling O_2 for plants.
> Breathing.
> Has lungs to breathe with.
> Air in. Air out.

These students and most of their peers provide a common-language definition for respiration, in which the term is used as a synonym for breathing, rather than a biological definition of cellular respiration. The consensus among the students is remarkable in view of the fact 91% of them had taken previous biology courses, but we have never seen a biology text that defines respiration in its common-language sense. Clearly, nothing they read in their biology texts was sufficient to alter their common-language definitions.

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[3]Biological usage of the term "respiration" is not entirely consistent. We use respiration to refer to the entire process by which glucose is oxidized to carbon dioxide and water. This is a common practice among biologists and in beginning biology texts. More advanced texts describe the oxidation of glucose as a two-step process: Glycolysis refers to the breakdown of glucose to pyruvate, and respiration only to the process in which pyruvate is oxidized to carbon dioxide and water.

2. Photosynthesis. Biologists define photosynthesis, like respiration, as a process involving both a sequence of chemical reactions and an energy conversion. The chemical reactions produce glucose and oxygen from carbon dioxide and water. The energy in sunlight is converted to chemical potential energy in glucose. In nontechnical terms, photosynthesis is the process by which plants use the energy in sunlight to make their own food.

Photosynthesis is unlike respiration in that the term has no non-biological meaning. Most students therefore responded to the pretest item asking them to define photosynthesis by attempting to remember what they had been taught about photosynthesis. This produced a wide variety of definitions:

> All I remember is it has to do with green plants and light.
> Plants take in CO_2 and change it to O_2.
> I remember needing to know a formula for it in high school.
>
> When the sun is directly on the plant--the plant will go through photosynthesis.
> Keeps plants green.
> Green plants turn sun and CO_2 into chlorophyll.

About 14% of the students taking the pretest mentioned glucose or food as a product of photosynthesis; 28% mentioned the conversion of sunlight to food energy or some equivalent form of energy.

3. Food. Like respiration, food is a term that is used in biological contexts with a meaning different from its common-language meaning. Food can be defined chemically, as a class of substances containing usable organic compounds, or functionally, as a class of substances that organisms can use as sources of energy for metabolism or materials for growth. Although organisms vary widely in the particular substances that they are capable of using as food, food shares these chemical and functional characteristics in all organisms. This biological definition of food is implicit in biologists' use

of concepts such as food chains and food webs and in the statement that plants are producers of food. It implies that water, carbon dioxide, and inorganic minerals are *not* food.

There were two questions on the pretest (numbers 7 and 8) in which students were asked to define "food for a bean plant" and "food for a person." Some typical student responses are listed below.

Student	Food for a Bean Plant	Food for a Person
John	Food for a bean plant is what is necessary for it to grow, water, soil & minerals, sunlight.	Food for a person is what is necessary to make us grow. Meat, vegetables, vitamins, water.
Jane	The chemicals it receives from the sunlight, soil, and fertilizer.	The kinds of things we eat.

Student	Food for a Bean Plant	Food for a Person
Jack	Sunlight, water, soil.	Energy we need to keep us going.
Jill	The nutrients in the soil. The sun, the water, other animals that died and their body becomes part of the soil.	Meat, milk, bread, vegetables, etc. Water.

A number of interesting patterns are apparent in these and other student definitions of food. The most obvious pattern is that students tend to define food as substances that plants, like animals, take in from their environment. Some version of this belief is nearly universal. Only 2% of the students answering Question 10 said that plants absorb "none" of their food through their roots, even though 17% answered Question 9 by saying that plants make "all" of their food inside their bodies!

A number of other patterns were less prevalent. It was not uncommon for people to respond to Questions 7 and 8 by listing substances that they considered to be food. "Sunlight" was commonly included on the lists by students who responded in this way, but carbon dioxide, another essential input to photosynthesis, appeared very rarely. Almost half of the students whose definitions associated food with energy said, like Jack, that food *was* energy. About 14% of the students taking the pretest provided essentially correct functional definitions of "food for a bean plant"; 25% provided appropriate functional definitions of "food for a person."

In summary, very few of the students taking the pretest could provide biologically acceptable definitions of respiration, photosynthesis, or food. Students tended to define and use "respiration" and "food" in ways that conformed with normal English usage, but not with acceptable biological usage. Their attempts to define photosynthesis often included fragments of an acceptable biological definition, but were rarely correct and coherent.

These difficulties with definitions can easily be dismissed as relatively insignificant. It doesn't *really* matter if students are confused about word usage as long as they basically understand how plants and animals function. Unfortunately, that seems not to be the case. Rather than being minor problems with word usage, the students' difficulties with definitions seem to be symptoms of more basic misconceptions about how plants and animals use matter and energy. Those more basic misconceptions are discussed in the next section.

Matter and energy in living systems. As we said in the introduction to this paper, respiration and photosynthesis are important because of the essential role they play in organisms' acquisition and use of energy for

metabolism and growth. They are also the basic processes in the carbon cycle, in which matter is converted from inorganic to organic forms and back again. If students understand the energy conversions and chemical transformations that take place during respiration and photosynthesis, then there is clearly little reason for concern about their problems with definitions.

Three issues concerning matter and energy in living systems are discussed below: Sources of energy for plants and animals, the nature of energy, and chemical conversions in plants and animals. The discussion is based primarily on data from this study only in the case of the first issue.

1. Sources of energy for plants and animals. According to biological theory, plants obtain metabolic energy from only one source: Sunlight. Animals obtain metabolic energy only as chemical potential energy in food.

There are three questions on the test that deal with sources of energy for plants and animals. Question 6 asks students if plants need light and asks them to explain their answers. Student responses to this question seem to indicate a reasonable understanding of the role that light plays in plants functioning. Ninety-one percent of the students say that plants need light, and 75% say that they need light to make food (10%), for photosynthesis (40%), or for energy (25%), all acceptable responses.

However, student responses to Question 4 reveal serious deficiencies in the understanding of most students. Although 90% of the students indicated that plants obtain energy from the sun, only 10% circled *only* the sun. The others indicated that plants obtain energy from other sources as well as the sun, such as water, soil, and fertilizer. Most students circled two or more choices in addition to "sun."

The pattern of responses to Question 5 was similar. The two correct options, "meat" and "potatoes" were circled by 94% of the students. However,

only 8% circled meat and potatoes *only*. The rest also circled incorrect responses such as air, water, sunlight, or exercise. Thus, students entering the course generally believed that both plants and animals obtain energy from a wide variety of sources in their environment.

2. The nature of energy. Like "respiration" and "food," "energy" is a term that has both a restricted scientific definition and a broader definition in common usage. There is evidence from other studies that students' difficulties in identifying the sources of energy for plants and animals are associated with misunderstandings about the nature of energy. We have found in our work on a variety of topics, including electricity, heat (Hollon & Anderson, 1985), and ecology (Brehm, Anderson, & DuBay, 1985), that students consistently have difficulty with problems involving energy conservation or energy transformations.

The difficulties involve confusion between forms of energy and other concepts that are not forms of energy. Thus students label as "energy" various kinds of matter (e.g., food, electrons, hot air), energy-conversion processes (e.g., photosynthesis), and other abstract concepts (e.g., force, temperature, voltage). The students' difficulties are almost always in the direction of being too inclusive (labeling as forms of energy things which are not) rather than not inclusive enough (failing to correctly identify forms of energy). This pattern is apparent in the students' responses to Questions 4 and 5, described above.

The students' commitment to such a broad and vague conception of energy has serious consequences for biological understanding. It renders them unable to see how energy is transformed and conserved during biological processes or to appreciate the uniqueness and importance of energy conversion processes such as respiration and photosynthesis.

3. Chemical conversions in plants and animals. Associated with the energy conversions of respiration and photosynthesis are conversions of matter from one chemical form to another. In photosynthesis two simple inorganic compounds, water and carbon dioxide, are combined to produce oxygen and glucose, a complex organic compound. Glucose, in turn, is combined with inorganic minerals from the soil to produce starches, cellulose, proteins, and all the other complex organic compounds of which a plant is made. The process is reversed in respiration; glucose is broken down and combined with oxygen to produce water and carbon dioxide. Although there are millions of processes in living systems in which organic compounds are converted from one form to another, photosynthesis and respiration are virtually unique in that they involve conversion of inorganic to organic compounds and vice versa. Photosynthesis is the primary process by which the organic matter of our world is created; respiration is the primary process by which it is destroyed.

Only one question on the pretest is directly relevant to student understanding of this issue. Question 12 asked students to draw molecular structures for the reactants and products in a very simple chemical reaction: $H_2 + Cl_2 \text{ -- } 2HCl$. Only 24% of the students were able to draw correct structures for the reactants (H-H and Cl-Cl); only 18% drew correct structures for the products (H-Cl and H-Cl). These findings replicate other research (Ben-Zvi, Eylon, & Silberstein, 1982; Yarroch, 1982) in which even students successfully completing high school chemistry courses were often unable to interpret simple chemical formulas and equations. One can imagine what they must make of the chemical formula for glucose: $C_6H_{12}O_6$.

It also appears that many students fail to conserve matter in their reasoning about chemical transformations, particularly those involving

invisible gases as reactants or products. For example, Hesse (in preparation) has found that many high school chemistry students explain that a burning match loses weight because it is "burned up" or "destroyed." Driver et al. (undated) found that 43% of the 15-year-old students in their study responded to a question asking where the mass in a growing tree came from with tautologies that did not answer the question: "As the tree grows it expands in all direction." Our interpretation of these answers is that the students simply are not paricularly concerned about where the mass of the tree came from. For them the tree "just grew" in the same way as for Hesse's students the match was "just consumed" by burning. The question of where the matter in a system comes from or where it goes is meaningful and important *only* to students who are firmly committed to conservation of matter during all chemical transformations. We do not believe that this commitment exists for all of our students.

In summary, we attribute students' difficulties with respiration and photosynthesis to fundamental misunderstandings of the functions of matter and energy in living systems. These misunderstandings involve not only biological processes but also basic physical concepts and principles: the conservation laws for both matter and energy, the nature of energy, and the atomic-molecular theory of matter.

Effects of Previous Instruction

The previous section contrasted accepted biological thinking with common student misconceptions about a variety of issues, including both definitions of key concepts and reasoning about the underlying processes that those processes describe. In this section we address the second research question: How successful has instruction in biology been in altering students' misconceptions?

We addressed this question by comparing students' test responses with their responses to the questionnaire about their previous biology experience. The test did not provide adequate data about all of the issues discussed in the previous section; it was possible to make reasonable assessments of student understanding for five different issues: students' definitions of (a) respiration, (b) photosynthesis, and (c) food, (d) understanding of plants' and animals' sources of food, and (e) understanding of plants and animals' sources of energy. Table 1 presents data on percentages of students that we classified as exhibiting either full or partial understanding of each goal conception on the pretest and posttest. Table 2 gives percentages of students classified as exhibiting full understanding only. A number of comments are presented below about the data in Tables 1 and 2.

Student sample. Students taking the test were a random sample of students attending laboratory sessions on the day the test was given. Since attendance at laboratory sessions was quite high, the sample closely approximated a random sample of students in the course. A few students whose tests were incomplete or whose answers were uninterpretable were eliminated from the sample for each question. The percentages in the tables are the percentages of students whose responses to the relevant question(s) were complete and interpretable.

Although this was a nonmajors' biology course, most students had taken several previous biology courses. The mean time spent in previous biology courses for students in the sample was 1.90 years. The median was 1.66 years (typically 1 year of high school biology and 2 terms of required biology courses at Michigan State). Less than 5% of the students had taken no previous biology.

Table 1

Percentage of Students Demonstrating Full or Partial Understanding of Five Issues Associated with Respiration and Photosynthesis

Definition/ Description	Question No.	Typical Naive Conception	Goal Conception	Previous Biology Course (years)					
				0-1		1-2		2 or more	
				Pretest *n*=22 (%)	Posttest *n*=19 (%)	Pretest *n*=43 (%)	Posttest *n*=38 (%)	Pretest *n*=40 (%)	Posttest *n*=37 (%
Respiration	1	Breathing exchange of CO_2 for O_2	Process by which organisms break down food (glucose) to extract energy	9	71	19	63	25	83
Photosynthesis	3	(Confused attempts to remember previous biology)	Process by which plants use the sunlight's energy to make food (glucose)	65	68	60	94	50	87
Food	7,8	Stuff that plants and animals take in from the environment because they need it	Organic matter that provides energy for metabolism (and materials for growth	47	80	26	77	41	80
Food source for plants	9,10, 11	Plants obtain some food from their environment	Plants make all of their food. They obtain (inorganic) raw materials from their environment	6	53	14	63	16	63
Source of energy for plants and animals	4,5,6	Plants and animals each obtain energy from a variety of sources	Plants obtain energy only from sunlight; animals obtain energy only from food	14	55	23	33	22	49

Note: In pretest, N=105; in posttest, N=94.

Table 2

Percentage of Students Demonstrating Full Understanding of Five Issues Associated with Respiration and Photosynthesis

Definition/ Description	Question No.	Typical Naive Conception	Goal Conception	Previous Biology Course (years)					
				0-1		1-2		2 or more	
				Pretest *n*=22 (%)	Posttest *n*=19 (%)	Pretest *n*=43 (%)	Posttest *n*=38 (%)	Pretest *n*=40 (%)	Posttes *n*=37 (%
Respiration	1	Breathing exchange of CO_2 for O_2	Process by which organisms break down food (glucose) to extract energy	0	35	16	21	10	38
Photosynthesis	3	(Confused attempts to remember previous biology)	Process by which plants use the sunlight's energy to make food (glucose)	0	15	4	21	0	32
Food	7,8	Stuff that plants and animals take in from the environment because they need it	Organic matter that provides energy for metabolism (and materials for growth	11	33	13	31	11	28
Food source for plants	9,10, 11	Plants obtain some food from their environment	Plants make all of their food. They obtain (inorganic) raw materials from their environment	6	23	0	11	0	23
Source of energy for plants and animals	4,5,6	Plants and animals each obtain energy from a variety of sources	Plants obtain energy only from sunlight; animals obtain energy only from food	0	38	5	11	5	32

Note: In pretest, N=105; in posttest, N=94.

General level of student understanding. Tables 1 and 2 offer two alternate assessments of the students' understanding of respiration and photosynthesis. For each issue there was a group of students whose answers had clearly been influenced by scientific reasoning, but who failed to provide complete and consistent renderings of the goal conceptions. These students were classified as exhibiting "partial understanding;" they are counted on Table 1 but not on Table 2.

In some cases, students classified as exhibiting partial understanding gave answers that were correct but omitted important ideas. For example, a number of students defined respiration in ways that included the oxidation of food or glucose, but failed to mention energy at all. In other cases students were classified in this group because of inconsistencies in their responses that gave us reason for serious doubt about the depth of their understanding. What should we make, for example, of the 35 students who said on the posttest that plants make "all" of their food inside their bodies (Question 9), but *also* said that they obtain "some" of their food through their roots or leaves (questions 10 and 11)? Our interpretation is that these students still retained some commitment to a naive definition of food or a naive understanding of plant function. Which definition they will remember about these issues a few years hence is not at all clear.

In general, we believe that Table 2 provides better estimates of the number of students who "understand" in the sense that (a) they can explain the processes of respiration and photosynthesis in a coherent and consistent manner, and (b) their beliefs are sufficiently well organized and internally consistent to assure long-term retention. Because no delayed posttest was given, we have no evidence to support the assertion about long-term retention.

In summary, the general level of understanding exhibited by students was not high on either the pretest or the posttest. Many students seemed to have achieved a partial understanding rather than a complete, fully integrated understanding of the scientific conceptions.

Effects of previous biology instruction. The amount of biology taken prior to the pretest had no apparent effect on student pretest performance or student posttest performance. The relationship between previous coursework and student understanding was not statistically significant at the .05 level for any of the five issues on either the pretest or the postest.

These data indicate that previous biology instruction seems neither to improve student performance on the pretest nor to prepare them to master these conceptions during the course. Since these are basic ideas that are "covered" in almost all beginning biology courses, the data lead us to question the effectiveness of biology instruction in our schools.

Effects of course instruction. The data reported in this paper were collected in conjunction with a curriculum development effort leading to the production of new teaching materials that were used in the course (Bishop, Roth, & Anderson, 1985). Course instruction using these materials led to improvements in student understanding that were at least detectable; students consistently did better on the posttest than on the pretest. Student posttest performance also improved after the new materials were introduced (Anderson, 1985.) However, the number of students fully understanding the scientific conceptions remained relatively low. After putting a major effort into developing course materials designed to help students overcome these misconceptions, we are quite impressed by the resilience of some of the misconceptions described above.

We attribute that resilience partly to the fact that the students' difficulties in understanding the biological processes are rooted in misunderstandings about concepts in the physical sciences: conservation of matter and energy, the nature of energy, and atomic-molecular theory. These difficulties with physical science conceptions were not adequately addressed by course instruction; thus students' understanding of the biological conceptions remained incomplete.

Conclusion

This study raises important questions about curriculum and instruction in biology. Respiration and photosynthesis play a basic role in a scientific understanding of biology, but most students are committed to misconceptions about the functioning of plants and animals. For the students in our non-science majors' course, it appears that current materials and practices in biology instruction leave those misconceptions virtually unchanged.

Our efforts to improve the effectiveness of instruction have produced measurably greater success than more traditional instructional methods (Anderson, 1985). The limited success of those efforts, however, has also led us to basic questions about the science curriculum. Many of the students entering this course had avoided courses in the physical sciences; others had taken those courses without mastering the basic ideas necessary for understanding of biological processes like photosynthesis and respiration. Thus the failure of physical science courses to attract and educate students who are not scientifically oriented ultimately inhibits their understanding not only of the physical sciences, but also of biology. Science educators must devise better ways of helping nonsience majors to overcome those barriers to understanding, for we are now wasting a great deal of everyone's time.

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Appendix

NUTRITION, RESPIRATION, AND PHOTOSYNTHESIS

1. How do you think a biologist would define the term "respiration"?

2. Humans engage in respiration.

   a. Which other living things engage in respiration? (circle all correct answers)

      snail bacteria rose plant cow mushroom

   b. Where in the human body does repiration take place? (circle all correct answers)

      muscles stomach lungs skin brain

3. How do you think that a biologist would define the term "photosynthesis"?

4. A bean plant needs energy to survive and grow. Where does the energy that a bean plant uses come from? (circle all correct answers & explain if necessary)

   air water sun soil worms & insects fertilizer

5. A human being also needs energy to grow and survive. Where do you think a person gets the energy he or she needs? (circle all correct answers & explain if necessary)

   air water sun exercise meat potatoes

6. Do plants need light? _____ Why or why not?

7. How do you define "food" for a bean plant?

8. How do you define "food" for a person?

In questions 9-11, circle the response you feel is most accurate. Use (?) only if you have no idea. If necessary, explain your answers in the space following the question.

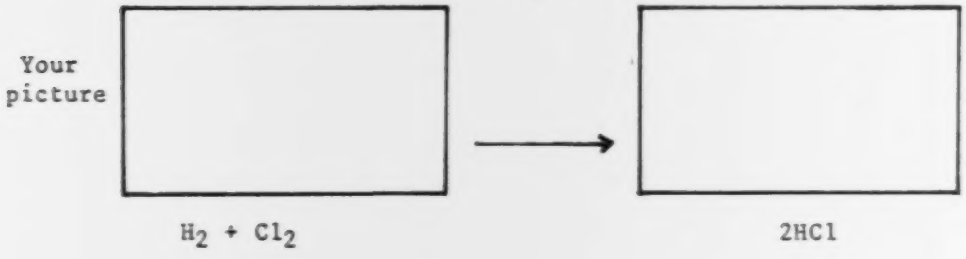
9. What portion of their food do bean plants get by making it inside their bodies? ALL SOME NONE ?

10. What portion of their food do bean plants absorb through their roots? ALL SOME NONE ?

11. What portion of their food do bean plants absorb through their leaves and stem? ALL SOME NONE ?

12. Let H represent an atom of hydrogen and Cl represent an atom of chlorine. Draw a picture to show how you think the atoms are bonded together for the reactants and products in the following equations:

$H_2 + Cl_2 \longrightarrow 2HCl$



13. Try to write sentences explaining the relationships among the following sets of terms. Write sentences including two terms if you do not feel that all three belong together.

a. respiration, photosynthesis, energy

b. photosynthesis, sunlight, food

c. respiration, energy, food

d. glucose, food, energy